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Program 1 **Environment Enhanced Fatigue of Advanced Aluminum Alloys and Metal Matrix Composites**

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Objective

The broad objective of this PhD research is to characterize and understand the environmental fatigue crack propagation behavior of advanced Al-Li-Cu based alloys and metal matrix composites. Aqueous NaCl and water vapor, which produce atomic hydrogen by reactions on clean crack surfaces, are emphasized. The effects of environment sensitive crack closure, stress ratio and precipitate microstructure are assessed. We seek mechanistic models of intrinsic crack tip damage processes to enable predictions of cracking behavior outside of the data, metallurgical improvements in material cracking resistance, and insight on hydrogen compatibility.

Environmental Fatigue of Alloy 2090 Sheet and Plate

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Abstract

Aluminum-lithium alloy 2090 (Al-2.7%Cu-2.2%Li-0.12%Zr in wt.%) is commercially available as sheet and plate. Enhanced near threshold fatigue crack growth rates have been found in reportedly recrystallized 2090 sheet compared to unrecrystallized 2090 plate in moist air. This effect was attributed to high levels of roughness induced crack closure in the 2090 plate due to textured grains and shearable δ'precipitates producing tortuous {111} slip band cracking in moist air. A low level of crack closure was found in the recrystallized sheet with a flat fracture path. These results were not compared based on ΔK_{eff} for R=0.75 ($R = P_{min}/P_{max}$), presumably due to the difficulties inherent in defining a single crack opening load from the load-displacement data for high R. The exact nature of the texture of grains, recrystallization, and possible texture in the sheet after recrystallization were not quantified. The analysis was not extended to determine the environmental influence which can be important in dramatically changing the cracking mechanisms.

This examination compares intrinsic fatigue crack growth rates and crack path tortuosity for 2090 sheet and plate in the unrecrystallized condition. A constant K_{max} of 17.0 MPa-m$^{1/2}$ was employed in the experiments to circumvent problems associated with defining crack closure levels. The role of grain size, texture, environment, and ΔK were explored. Experiments were performed in better than 6.5×10^{-6} pascal dynamic vacuum, in moist air, and in an aqueous 1 wt% NaCl solution at a fixed potential. For vintage III sheet, 1 wt% NaCl was found to be mildly more aggressive than moist air, and ΔK_{th} increased by a factor of 3X in a vacuum over moist air. Crack growth rates were enhanced in moist air by 10X over vacuum in the near threshold regime, with the difference decreasing to 2X for the higher ΔK ranges examined. Vintage III sheet and vintage III plate were found to have similar intrinsic fatigue crack growth rates in moist air with the plate exhibiting a more tortuous crack path with regions of slip band cracking and possible cleavage cracking. Vintage III plate was compared to an early vintage 2090 plate and a factor of 1.5 reduction in ΔK_{th} was observed for vintage III plate which is not understood.

Future work will center on clearly characterizing the texture through the material thickness, identifying the exact nature of the grain and subgrain structure, and further monitoring the cracking mode. Proportions of slip band cracking, cleavage cracking, and intersubgranular cracking will be indentified for each environment in sheet and plate specimens. Critical experiments that evaluate the exact nature of damaging cracking modes will be identified for 2090 or model alloy systems.

Environmental Fatigue of Alloy 2090 Sheet and Plate

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Alloy 2090 Background

Applications

- o Low density for aerospace applications
- o Available as plate and sheet

Characteristics

- o Al-2.7%Cu-2.2%Li-0.25%Mg-0.12%Zr (in wt. %)
- o Strengthening from θ' ($CuAl_2$), T_1 (Al_2CuLi), and δ' (Al_3Li)

- o Heavily textured during processing
- o Shearable coherent δ' can give Persistant Slip Bands (PSB)
- o Texture and PSB can lead to tortuous crack profiles

Fatigue Crack Characteristics of 2090

o Cracks along {111} PSB
  - Multiple {111} facets result in a tortuous crack path

o Transgranular crystallographic cracks along {100} or {110} planes

o Intersubgranular cracks along subgrain boundaries

o Intergranular cracks along grain boundaries

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o Proportion of cracking characteristics set by conditions
  - ΔK
  - Environment
  - Microstructure

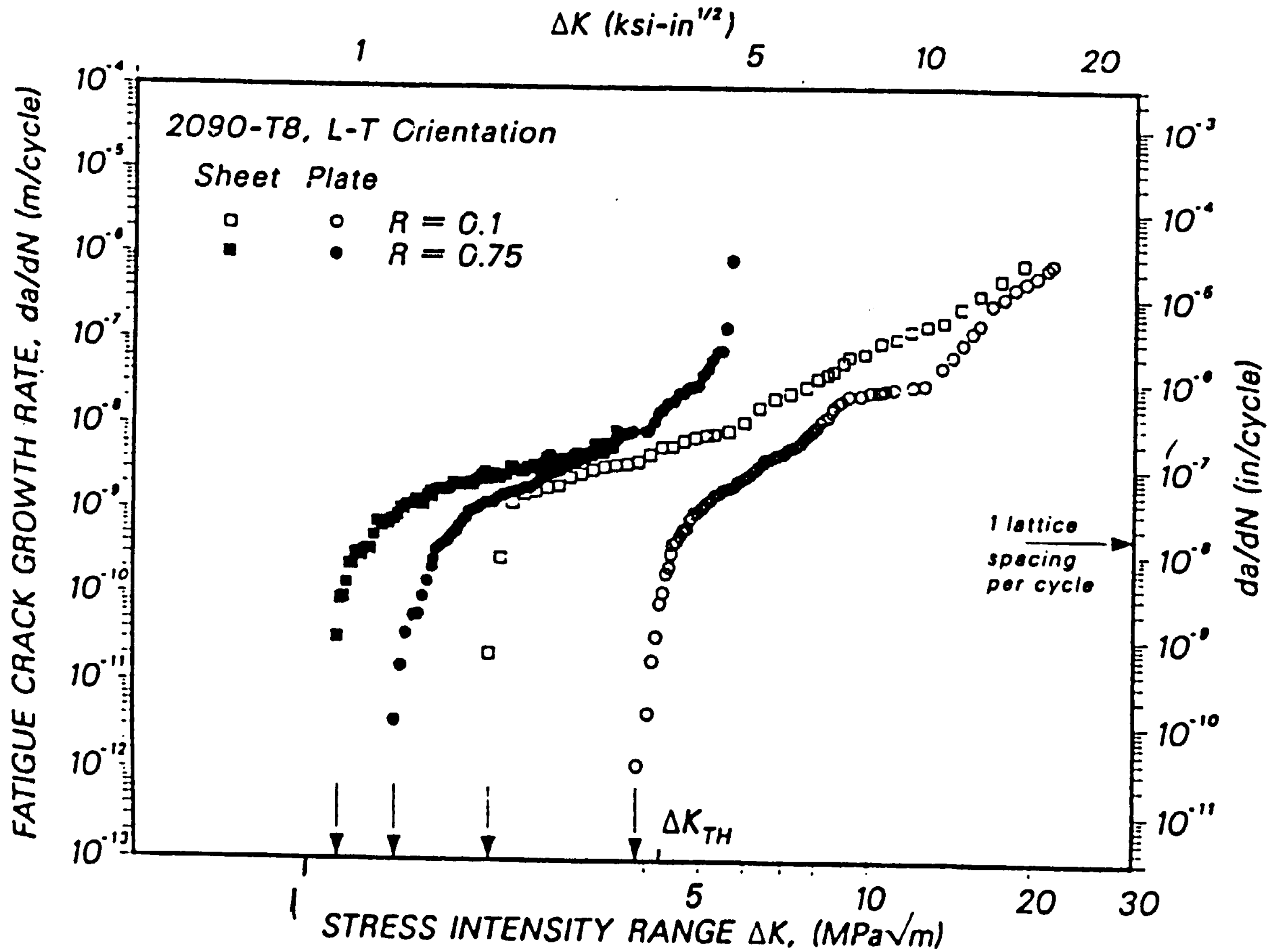
Initial Questions

- o What determines the amount of fatigue crack path tortuosity?
  - ΔK
  - Environmental influence (Piascik)
  - Processing dependence
  - Texture
  - "Grain size"
  - R-ratio

- o How are the intrinsic fatigue crack grow rates influenced by the microstructure, environment, and texture?
  - Crack growth rates
  - Shape of da/dN-ΔK Curve

2090 Sheet and Plate

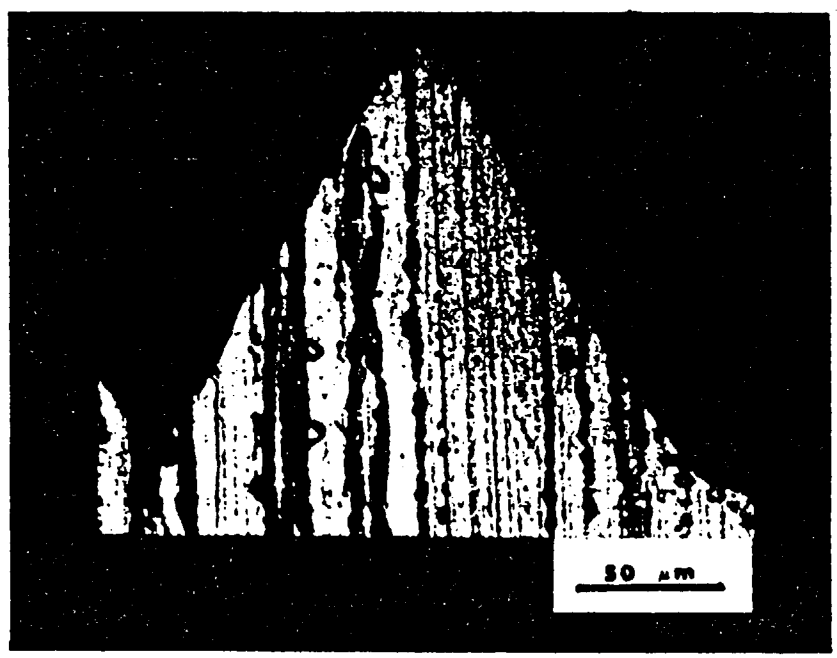
(After Venkateswara Rao, Bucci, Jata, & Ritchie)



2090 Slip Band Cracking in 13mm Plate

T-Plane

(After Yoder, Pao, Imam, & Cooley)



Procedure

o Characterize 2090 sheet and plate microstructures optically
- Vintage III 3.2mm Sheet (Age 18 hours at 155 C)
- Vintage III 19.0mm Plate (Age 18 hours at 163 C)
- 38.1 mm Plate (Age 4 hours at 190 C- Piascik)

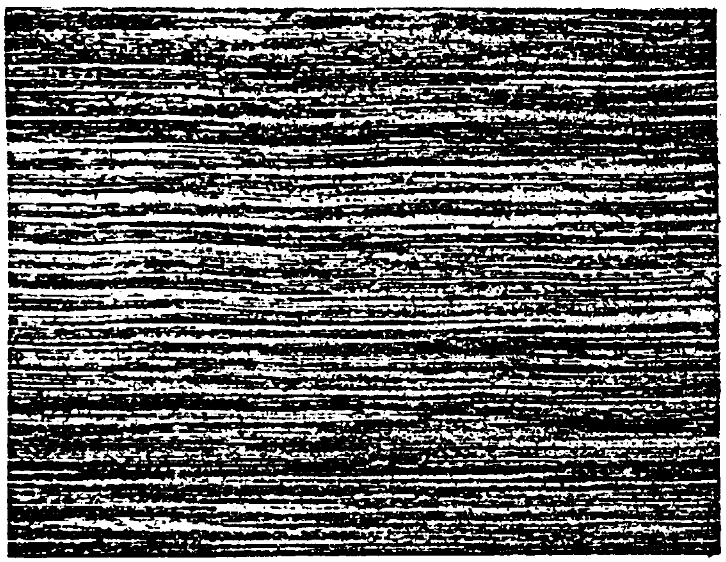
o Determine the texture
- Texture and texture gradients

o Measure intrinsic fatigue crack growth rates
- Vacuum
- Air
- Aqueous 1.0 wt.% NaCl

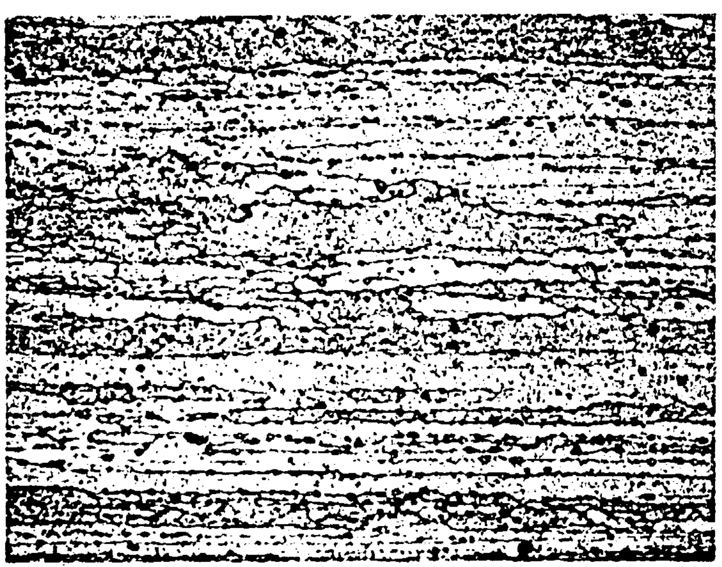
o Examine fracture surfaces

Sheet S-T Plane

Plate S-T Plane




500 μm




50 μm

Sheet Mid-Plane Texture

Recrystallized Textures

Cube {100}<001> 1.6X

Goss {110}<001> -.3X

Rolling Textures

Brass {110}<112> 30.8X

S {123}<634> 16.9X

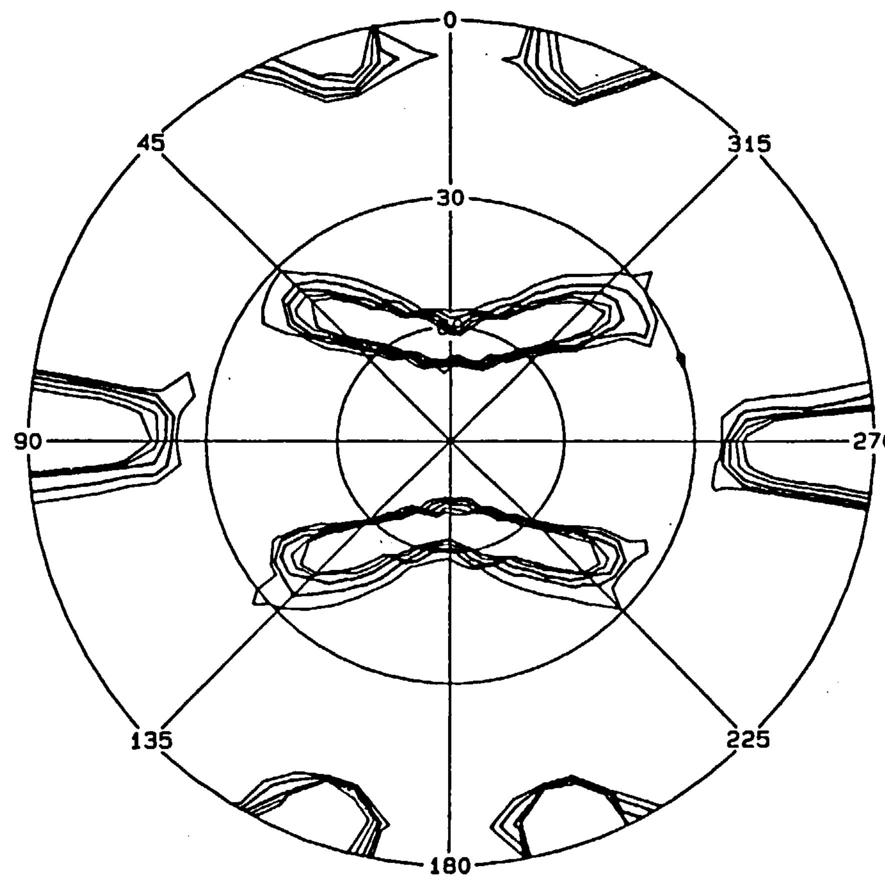
Cu {112}<111> 6.3X

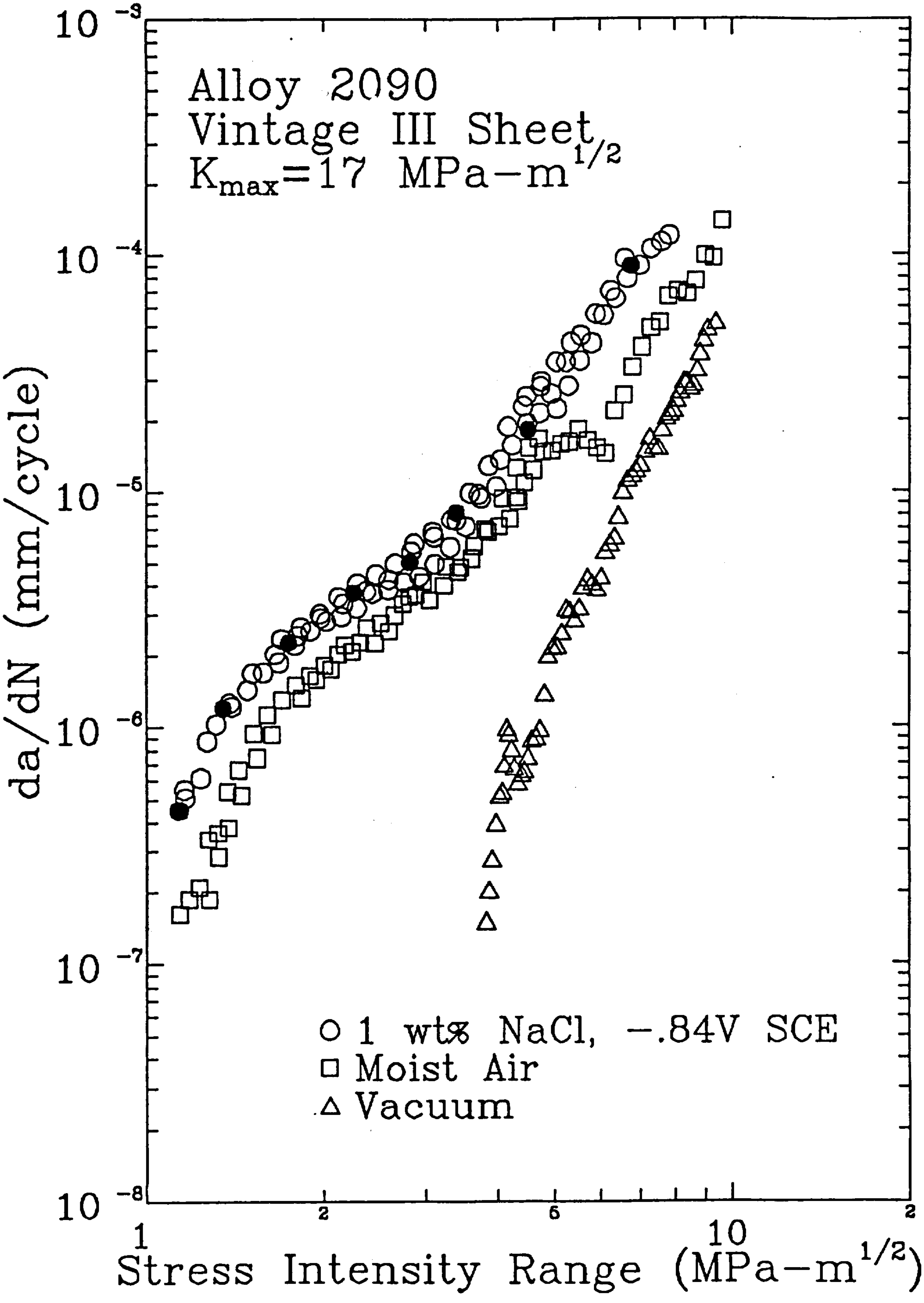
{ } = Rolling Plane = SN

< > = Rolling Direction = RD

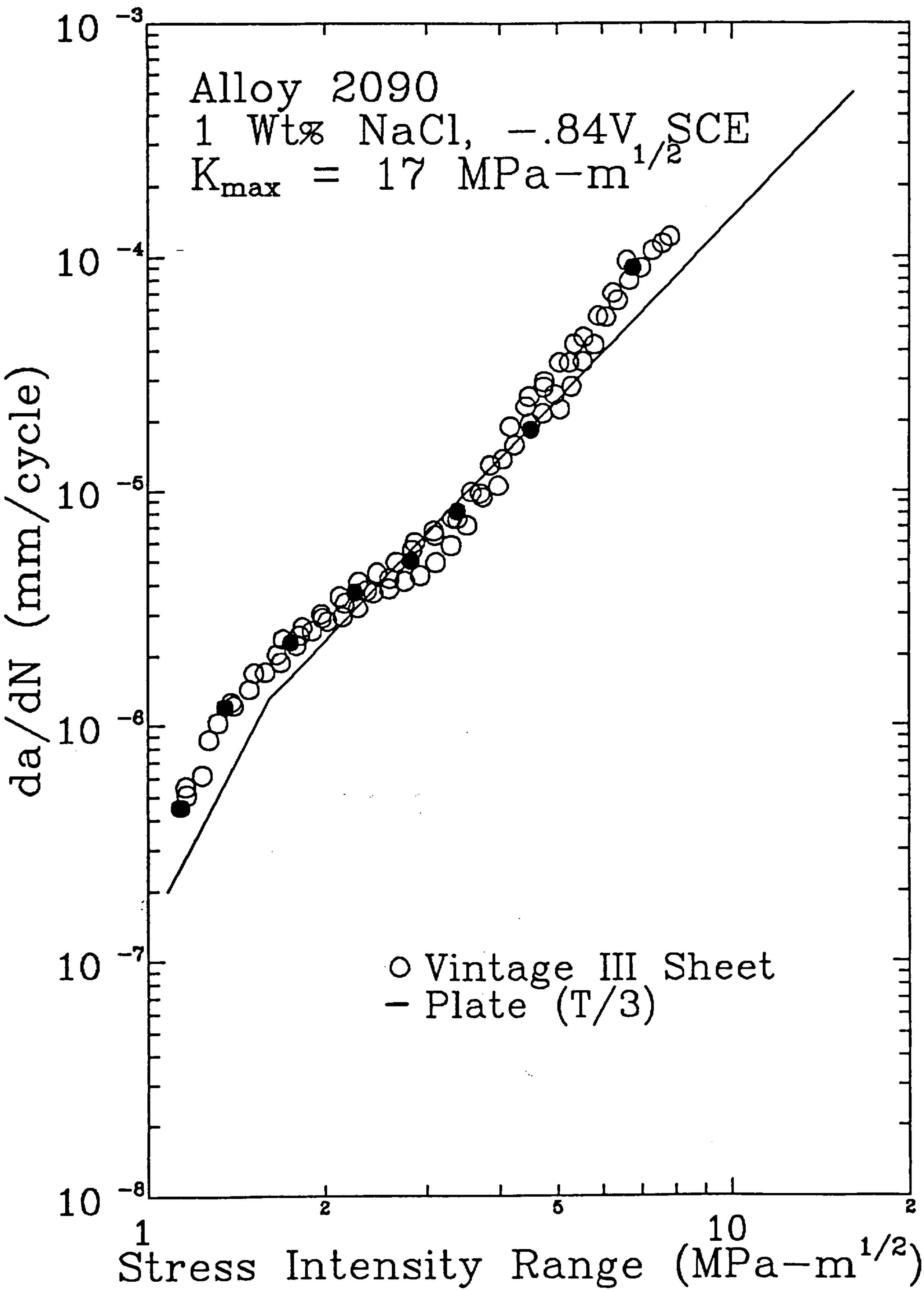
{111} Diffraction Conditions

RD

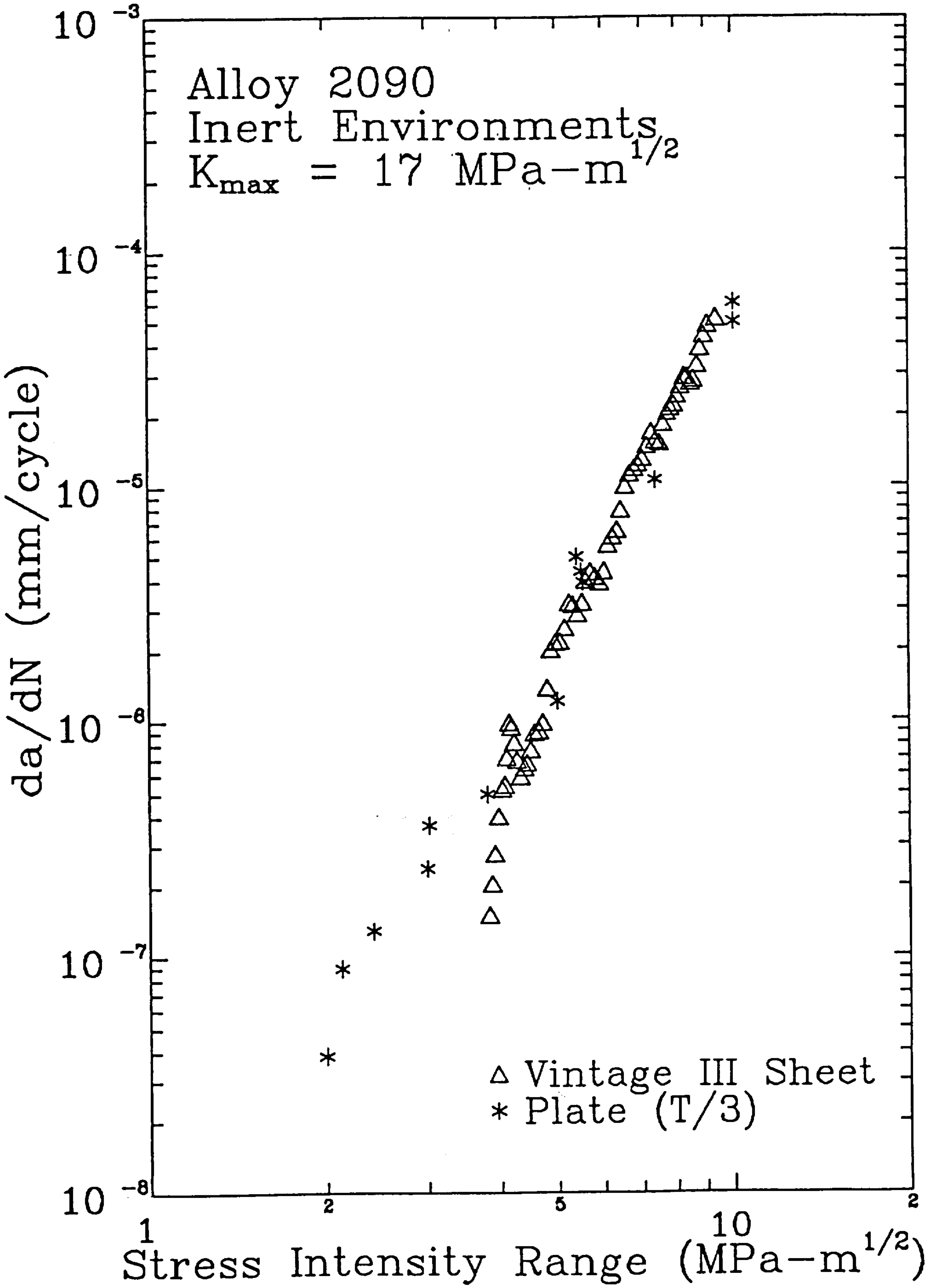


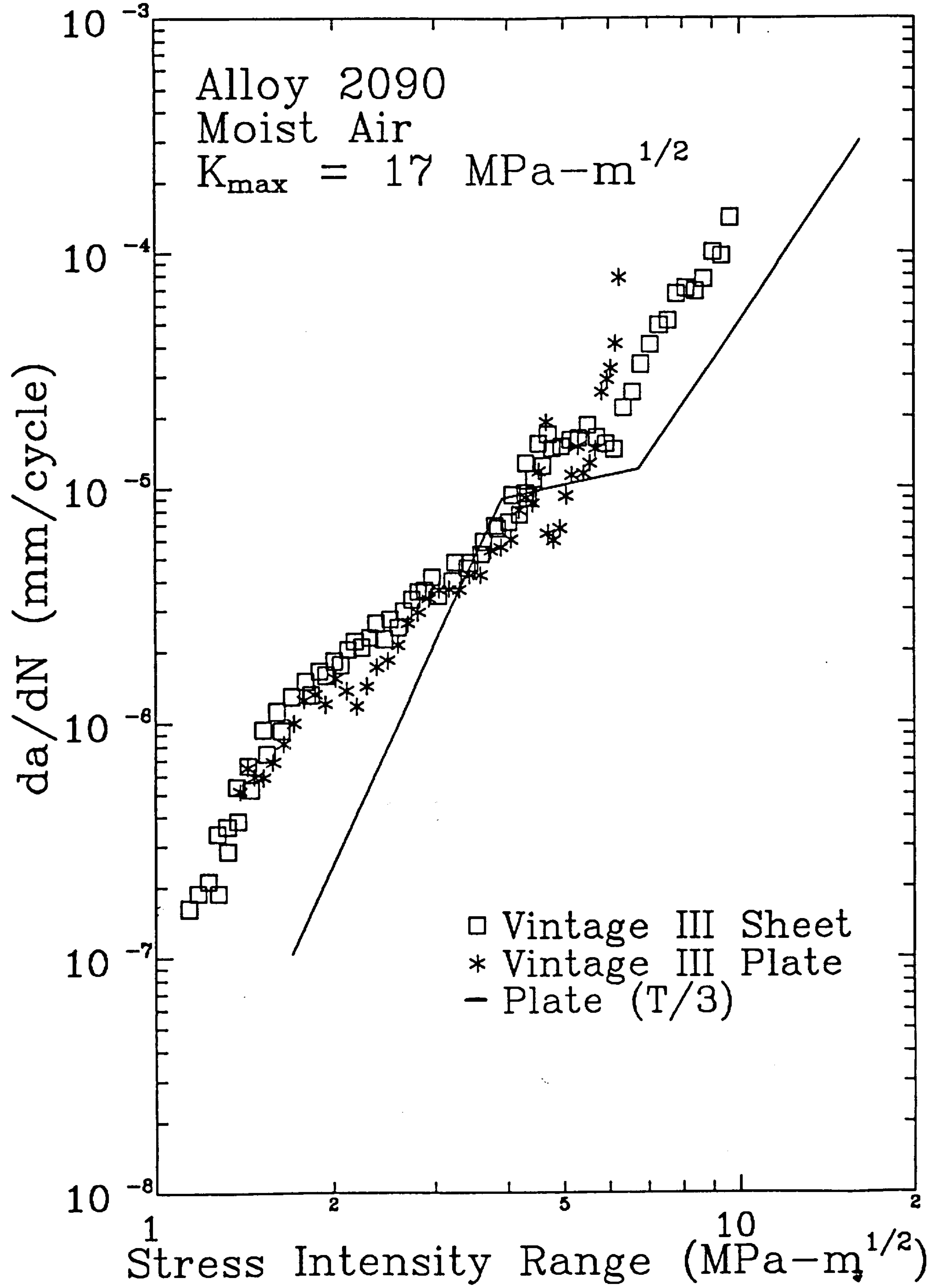


Alloy 2090
Vintage III Sheet
Kmax=17 MPa-m1/2
10 -3
10 -4
10 -5
10 -6
10 -7
10 -8
da/dN (mm/cycle)
1
2
5
10
2
Stress Intensity Range (MPa-m1/2)
1 wt% NaCl, -.84V SCE
Moist Air
Vacuum



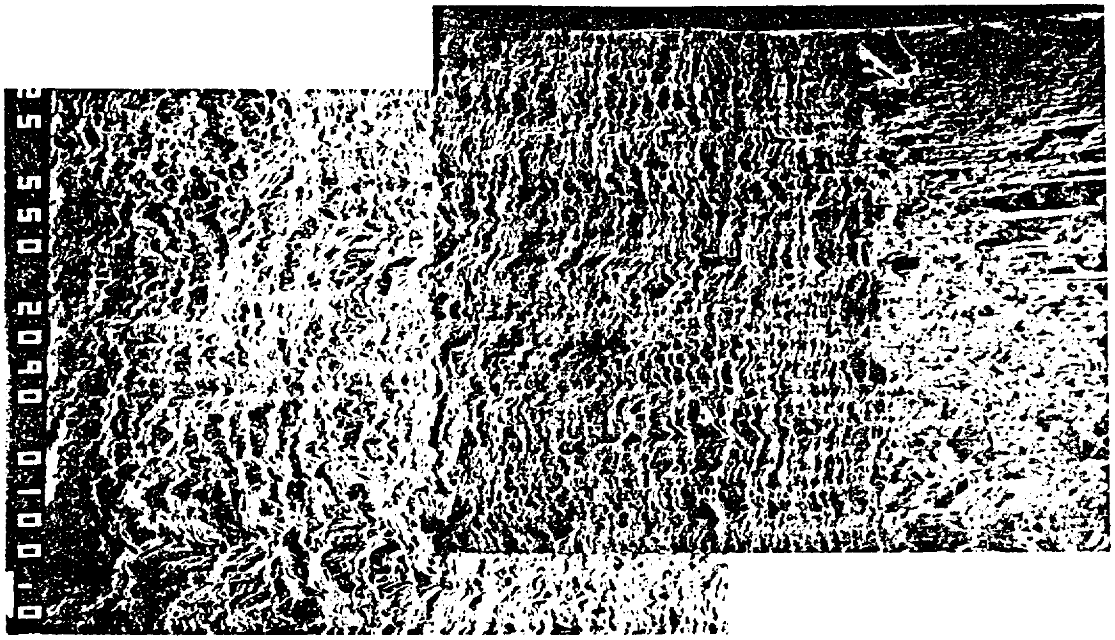
Alloy 2090
1 Wt% NaCl, -.84V SCE
K_{max} = 17 MPa-m$^{1/2}$
○ Vintage III Sheet
— Plate (T/3)
da/dN (mm/cycle)
Stress Intensity Range (MPa-m$^{1/2}$)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
2
5
10
2


Alloy 2090
Inert Environments
K_{max} = 17 MPa-$m^{1/2}$
△ Vintage III Sheet
* Plate (T/3)
da/dN (mm/cycle)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
2
5
10
2
Stress Intensity Range (MPa-$m^{1/2}$)



Alloy 2090
Moist Air
K_{max} = 17 MPa-m$^{1/2}$
da/dN (mm/cycle)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
2
5
10
2
Stress Intensity Range (MPa-m$^{1/2}$)
□ Vintage III Sheet
* Vintage III Plate
— Plate (T/3)

2090 Vintage III Sheet in Air



Crack Direction

0.5 mm

2090 Vintage III Plate (T/2) in Air

0.5 mm

Conclusions

- o A reliable experimental setup has been used to measure intrinsic fatigue crack growth rates in sheet specimens.
  - Vacuum
  - Moist air
  - Aqueous 1.0 wt% NaCl

- o For 2090 sheet, ΔK_{th} was a factor of 3 higher in a vacuum as compared to moist air.

- o For 2090 sheet, aqueous 1 wt. % NaCl was only mildly more damaging as compared to moist air.

2090 Intrinsic Crack Growth Rate Conclusions

- o Vintage III plate versus vintage III sheet
  - Moist air equivalence
  - Some SBC with crack features scaling to the microstructure
- o Plate versus vintage III sheet
  - In vacuum higher ΔK_{th} for vintage III sheet
  - In moist air higher ΔK_{th} for plate
  - Aqueous 1.0 wt% NaCl similar
- o Plate versus vintage III plate
  - Significant difference in moist air
  - 190 C age not the cause

Future Questions

o What dramatically influences intrinsic fatigue crack growth rates in inert and aggressive environments?

- R-ratio
- Sheet versus plate texture and/or microstructure
- Effect of ageing condition

o What factors determine the the crack path?

- Environment
- ΔK, R-ratio
- Microstructure (precipitates, grain size, grain orientation)
- Texture

o What is the microscopic damage process for a given crack path?

o What is the basis and approach toward predicting da/dN versus ΔK?